Onboard Data Summarization and Long-term Onboard Archives for Long-Duration Missions

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ABSTRACT

This paper describes how onboard data summarization will be used as part of an overall knowledge management approach for long duration JPL missions. Onboard summarization and adaptive operations are currently being flight validated on the Deep Space One (DS1) mission as the primary components of the Beacon Monitor Operations Experiment. Beacon operations is a spacecraft-initiated operations concept that is widely applicable to deep space missions and has been baselined for upcoming NASA missions to Europa and Pluto. Since beacon operations implies that the spacecraft determines when ground intervention is necessary, implementing the concept requires specific strategies for onboard data collection, downlink determination, and long-term onboard storage. Onboard summarization (whether or not the beacon operational concept is used) can reduce operational cost, provide the flight system with access to critical past events, and archive data that is not normally downlinked so it can be retrieved manually by ground personnel if necessary. Migrating these data analysis functions to the spacecraft has a substantial impact on how knowledge is managed for a given mission.

1.0 INTRODUCTION

At design-time, the onus is on both the ground and flight segments to provide capabilities that enable the mission to be conducted cheaply and reliably. This has given rise to a research effort at JPL for developing the operational concept and associated technology components required to implement highly adaptive, spacecraft-initiated operations. Current work in this area has culminated in the successful deployment of the Beacon Monitor Operations Experiment on the Deep Space One (DS1) Mission. This experiment, which is currently active, implements a capability that enables the spacecraft to determine when tracking is required, transmits that information to the ground using an sub-carrier beacon signal, and then transmits intelligent data summaries after the beacon tone has requested a telemetry track. This technology is relevant to many types of missions, but especially deep space missions since these tend to be more bandwidth limited. The beacon operational concept is baselined for Pluto and Europa missions and is also planned for inclusion in the DS1 extended mission. Adaptation of the deep space operational concept to earth-orbiting missions is being pursued by both Stanford University and the University of Colorado.

The software flown on DS1 creates event-driven summaries of spacecraft events since the last contact. Episodes are created by identifying the culprit and causally related sensors around the time of important events. This data is gathered at a high sample-rate, assigned a priority, and stored for downlink at the next telemetry pass. The gaps are filled-in by "snapshots" of all sensor channels at a much lower sample-rate. The software can use either traditional (static) alarm thresholds or adaptive alarm limit functions that are determined by a neural network. The adaptive alarm limit technology, called ELMER (Envelope Learning and Monitoring using Error Relaxation) is one of two AI components in the current software design. The second AI-based method computes empirical transforms on individual data channels. These pseudo-sensors enhance the value of summaries and serve as an additional input in determining the adaptive limits.

This paper describes the DS1 summarization system for context but also looks beyond the scope of what has currently been developed to address broader knowledge management issues over the life of the mission. *Planned missions to Europa and Pluto will only downlink approximately 5% of all engineering data gathered onboard.* It becomes imperative, therefore, to develop software that not only summarizes what information should be sent back to Earth, but also summarizes for the purpose of creating a long-term archive that will be maintained onboard throughout the mission. Given that onboard data storage hardware is sized for the large amount of science data that will be acquired at the target body, for most of the mission this storage space would go unused anyway. There is in fact much more available storage than bandwidth at each downlink opportunity. What this means is that maintaining an archive onboard can enable storage of higher-resolution and/or more complete data sets than would be sent to Earth. This can benefit the mission in many ways, from both cost and risk standpoints. The ability to have more comprehensive fault protection systems that refer to historical data onboard the spacecraft can enable long-term, automated, space-based trend analysis to occur. During anomalies, onboard access to historical data can reduce the risk incurred from the time delays associated with deep space communication. Onboard archives also have the advantage of being able to reduce the risk and cost associated with maintaining personnel skills and managing turnover common in multi-year flight project operations. One should keep in mind that summarization strategies will likely evolve over the life of a mission resulting in periodic flight software updates. DS1 has shown that such updates for future missions are likely achievable at low cost and low risk.

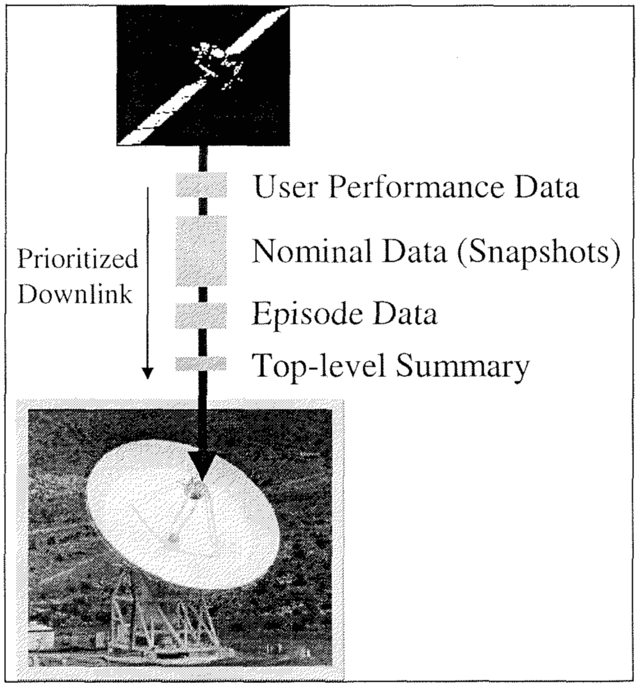
2.0 ONBOARD SUMMARIZATION TO REDUCE DOWNLINK

Flight Software

If the beacon tone indicates that tracking is required, the onboard summarization system provides concise summaries of all pertinent spacecraft data since the previous contact. The software is comprised of several algorithms that are layered upon the baseline telemetry management software for the spacecraft. A mission activity subroutine determines the overall spacecraft mode of operation so that the appropriate set of alarm limits can be applied. A data collection subroutine receives data from the engineering telemetry system via function calls, applies summary techniques and computes transforms as directed. These transforms are computed by applying standard functions, such as minimum, maximum, mean, first derivative, and second derivative to the sensor data. Transforms are treated as pseudo-sensors and can be used for anomaly detection or as an input to other onboard software. The episode subroutine combines summary and engineering data received internally from the data collection subroutine with the mission activity received from the activity subroutine and compares the data with mission activity specific alarm limits. It is necessary to use the mission activities to determine which data to use for episode identification and to identify the alarm limits for this data. If the limit is exceeded, the subroutine spawns a new episode and collects past relevant data from the data collection subroutine. The past data is a series of one-minute summaries that go back in time as far as the user has defined. For example, a five-minute episode contains summaries starting five minutes before the episode to five minutes after the episode. At the end of the episode, the subroutine outputs data to the telemetry subsystem for downlink.

The version of the software currently being flown on DS1 has the capability to use AI-based envelope functions instead of traditional alarm limits. This system, called ELMER (Envelope Learning and Monitoring using Error Relaxation), provides a new form of event detection and will be evaluated in addition to using the project-specified traditional alarm limits. Envelope functions are essentially adaptive alarm limits learned by training a neural network on nominal engineering data. The neural net can be onboard or on the ground. For DS1, envelope functions are trained on the ground and then uploaded to the spacecraft. The summaries are generated at regular intervals and stored in memory until the next telemetry ground contact. When a ground contact occurs, the information shown in Figure 2.1 is transmitted.

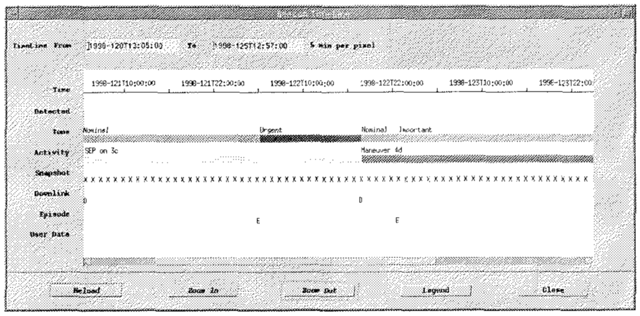
Figure 2.1
Summary System Downlinked Data



Ground Software

BeaVis (BEAcon VISualization) is a ground-based display environment for viewing summary data and tone state histories. The tool was designed to facilitate quick interaction with data that has been summarized in a remote system. Summary data files (as downlinked telemetry for space missions) contain all of the important information since the last contact. While it is possible that the summary information is just providing confirming status information, for an adaptive or autonomous system there is likely some urgency in understanding the data because in many circumstances, it would not have been sent in the first place if the remote system was functioning normally. For this reason, it was imperative that we devise a solution that would enable an operator to quickly evaluate summary data in order to arrive at the best possible diagnosis of system behavior. The challenge here is shared between the remote system's ability to summarize and the ground system's ability to present the information logically to the user.

Figure 2.2
BeaVis Timeline Display



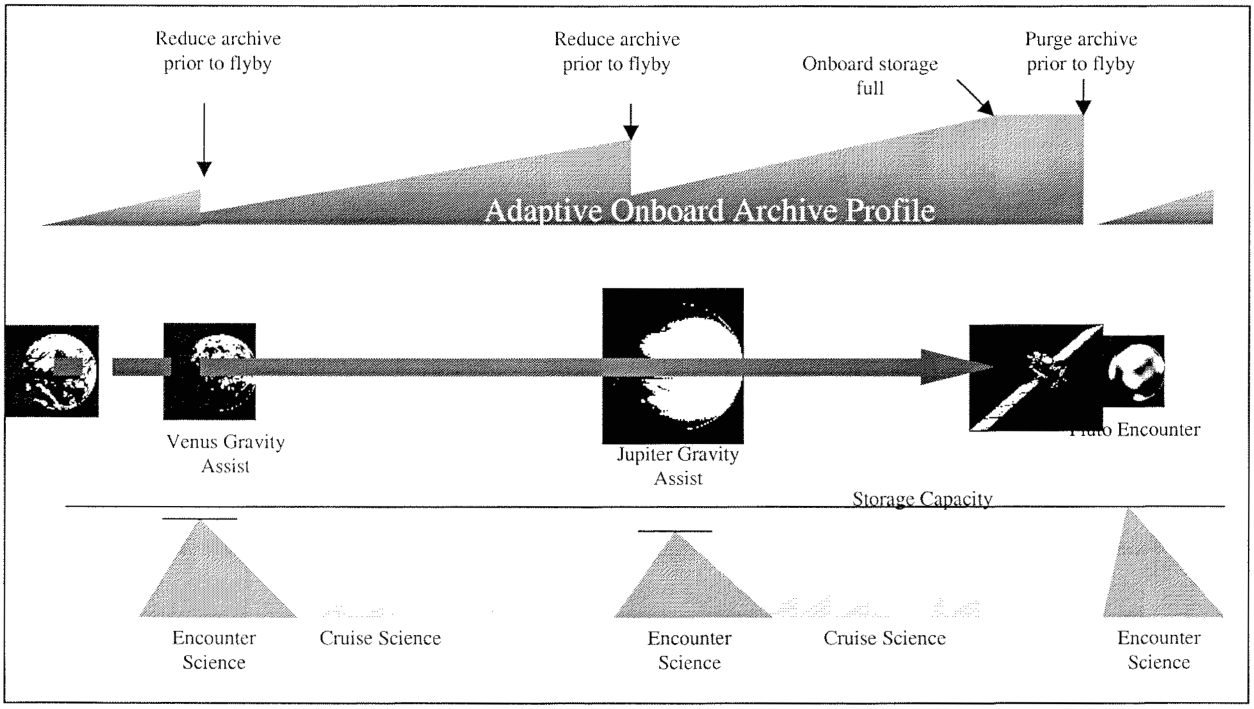
The BeaVis delivery for DS1 provides several novel ways of visualizing summary information and includes a timeline display, tabular displays and strip charts. The timeline display, shown in Figure 2.2, provides access to summary downlink data and indicates beacon tone detections that have transpired during the mission. There are GUI elements that show specific summary data components, such as mission activity changes, snapshot telemetry, episode data and user summary data. These serve as "hypertext" style links to the more detailed tabular and strip chart displays of summary data channels. The environment also includes a tool for creating the parameter tables that are uploaded to the spacecraft.

3.0 ONBOARD SUMMARIZATION FOR ONBOARD ARCHIVING

Typically, deep space mission storage is sized for encounter and is largely unused during cruise. This storage capacity can be treated as a valuable resource because it can be used to store spacecraft health data that would otherwise be lost. Much of our current research into onboard summarization software for downlink is also applicable to the creation of long-term archives that would be maintained onboard the spacecraft. Developing initial concepts for archiving involve understanding various aspects of mission design, defining specific algorithms for summarization, and creating an archive data manager as a higher level software component over the spacecraft telemetry management system.

Figure 3.1 is an example scenario that shows how onboard data storage resources may be utilized during a mission to Pluto. Each triangle in this graphic depicts the volume of storage per unit of time. The important point in this graphic is that archives must be actively managed throughout the mission operations lifecycle. Determining what data goes into the "green wedges" in Figure 3.1 is the specific challenge addressed by onboard summarization technology. Note that the chart shows that archives are reduced (not eliminated) during gravity-assist flybys along the trajectory and all of the archive is deleted at the final encounter. What this means is that, for this example, the mission operations team has decided to preserve some of the archive during flybys to mitigate mission risk. The exact regime employed would be determined by several factors, including the risk tolerance of the mission management, cost constraints, mission performance, and spacecraft operability constraints.

Figure 3.1
Onboard Data Management
Scenario



In order to create profiles for onboard archives as shown in Figure 3.1, an archive data manager is needed. This piece of software determines the proportion of each type of information in the archive, adjusts data resolution (sample rate) and adds/deletes data as necessary to attain the objectives of the archive at any point in the mission. The archive data manager "weeds out" data when memory is deemed full, as depicted in Figure 3.1 after the Jupiter flyby. The software also purges or reduces the archive to make room for science data as required. The data manager can be queried to show at a high-level what data is in the archive at any given time and this software module is also the primary interface for retrieving data from the archive.

After deciding at design-time that data will be archived onboard throughout the mission, there are many choices on how to do this archiving. Figure 3.2 summarizes some of the key archive components currently being evaluated. As previously stated, algorithms developed for downlink summarization can be directly applicable to archive summarization. Specifically, episodes, snapshots, transforms, performance data, state histories, ELMER, and event logs are applicable to both. More sophisticated onboard trend tracking software can be developed to replace ground-based routine trend monitoring. The notion of a history bank is important for caching recent bulk data in the event that downlinked summaries are not sufficient for troubleshooting problems. The history bank can also be a particularly useful input to onboard autonomy components, such as planners, schedulers, executives, and automated fault detection isolation and recovery software. History bank data can itself be maintained at varying resolution based on age and/or perceived importance to the mission.

Figure 3.2
Components of the Archive

Component	Description
Episodes	Culprit and causally related sensors (at high sample-rate) around the time of anomalies
Snapshots	All sensors and transforms sampled very infrequently throughout the mission
Transforms	Empirical and/or model-based transforms on raw sensor channels
Trends	Maintain awareness of slow trends in sensor data
Performance Data	Similar to episodes but document performance during nominal events
State Histories	Spacecraft mode histories and other state information pertinent to onboard software
Event Logs	Precise logging of spacecraft command actions around the time of anomalies, especially for autonomous system diagnosis and troubleshooting
Recent History Bank	Data that may be of use to ground personnel if downlinked summaries are not sufficient

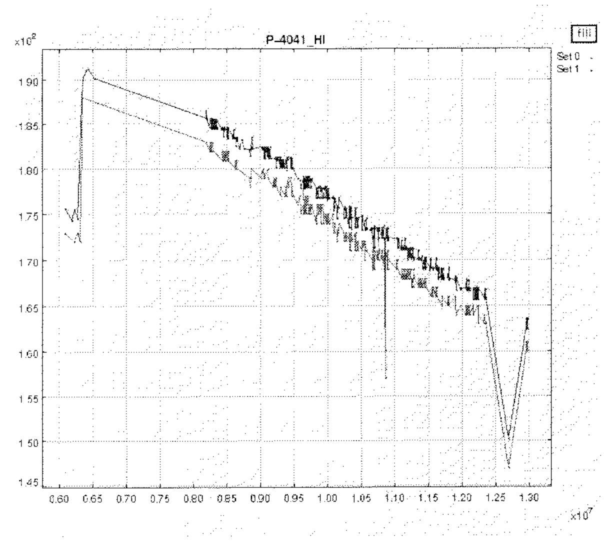
4.0 RESULTS TO DATE

Onboard summarization for DS1 was the first major effort in this technology area for NASA. The flight software and the beacon operations concept have been 100% validated and operational effectiveness assessments are currently being conducted. The initial set of summarization data included 97 ‘engineering’ sensor values sampled onboard once per second. These values were chosen based on their importance in detecting major spacecraft anomalies. Five additional sensor values were derived from the original set. Functions including minimum, maximum, mean, first derivative, and second derivative were applied to 16 of the original sensors. High and low limits were applied to 33 of the sensor values. Results to date are indicating that data summarization software provides enough detail for spacecraft engineers using the beacon ground visualization tools to respond appropriately.

Another activity that is producing important results involves analyzing the summary system performance on DS1 anomalies to date. Preliminary results when running ELMER on DS1 historical data are showing that adaptive alarm thresholds can track gradual trending of sensor data much tighter than the current DS1 static alarm limits. We see this in monitoring the gradual drift in eight solar array temperatures sensors, one of which is shown in Red in Figure 4.1. In comparing traditional limits with the ELMER upper adaptive limit (shown in Blue) during 81 days of operations, we see that the ELMER limit tracks actual spacecraft performance much more precisely than the static limit, which would be off the scale of this chart.

Figure 4.1
Tracking of adaptive alarm limit to
DS1 solar array temperature

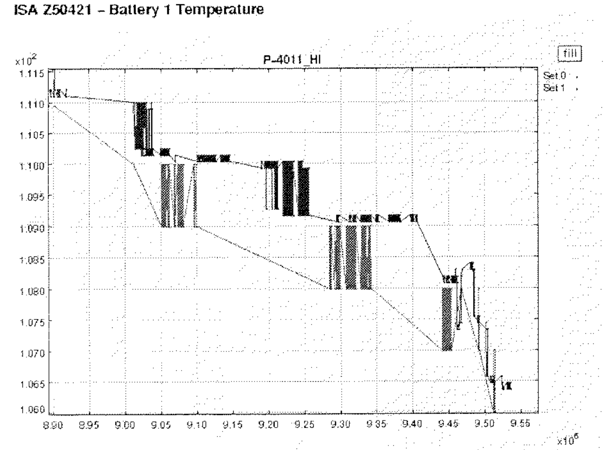
ELMER Handling Sensor Drift



Another validation exercise is confirming that summarization can capture subtle, yet important spacecraft epsiodes. In ground tests, ELMER detected a unexpected heater turn-on that occurred when the solar panels went off-axis during a spacecraft maneuver. Since ELMER trains across multiple parameters using nominal data, the summarization system detected this event without explicit a priori knowledge of the scenario. This data is shown in Figure 4.2 (sensor value in Red, adaptive limit in Blue).

Figure 4.2
Battery Temperature Episode Detection

ISA Z50421 - Battery 1 Temperature



5.0 FUTURE WORK

Much of our research in the coming year will focus on next generation onboard summarization and long-duration archiving. The products of our research will be delivered to the JPL Mission Data System program for use on outer planet missions. Europa Orbiter is the first customer, requiring an initial flight software delivery in November of 2000. We will also continue to evaluate how onboard capabilities mesh with overall knowledge management approaches for these missions. In addition to the research activities, we will continue to obtain hands-on experience operating summarization systems through infusion of beacon operations and onboard summarization into the two year DS1 extended mission scheduled to begin in September of 1999.

6.0 ACKNOWLEDGEMENT

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7.0 REFERENCES

Doyle, R. et. al: "Autonomy and Software Technology on NASA's Deep Space One," *IEEE Intelligent Systems Magazine*, May/June 1999.

Sherwood, R., et. al: 1999, "Lessons Learned During Implementation and Early Operations of the DS1 Beacon Monitor Experiment," *Third International Symposium on Reducing the Cost of Ground Systems and Spacecraft Operations*, Tainan, Taiwan.

Wyatt, E. J., et. al: 1997, "An Overview of the Beacon Monitor Operations Technology," *International Symposium on Artificial Intelligence, Robotics, and Automation in Space*, Tokyo, Japan.

Wyatt, E. J., et. al: 1998, "Beacon Monitor Operations on the Deep Space One Mission," *Fifth International Symposium on Space Mission Operations and Ground Data Systems*, Tokyo, Japan.

DeCoste, D.: 1997, "Automated Learning and Monitoring of Limit Functions," *International Symposium on Artificial Intelligence, Robotics, and Automation in Space*, Tokyo, Japan.

Sherwood, R., et. al: 1997, "Flight Software Implementation of the Beacon Monitor Experiment On the NASA New Millennium Deep Space 1 (DS1) Mission," *Second International Symposium on Reducing the Cost of Spacecraft Ground Systems and Operations*, Oxfordshire, UK.

Chien, S., et. al: 1997, "Resource Scheduling for a Network of Communications Antennas," *Proceedings of the IEEE Aerospace Conference*, Aspen, CO.

Staehle, R.L., et. al: 1996, "Pluto Express: Advanced Technologies Enable Lower Cost Missions to the Outer Solar System and Beyond," *International Low Cost Planetary Missions Conference*, Laurel, MD.

Wyatt, E.J. and J.B. Carraway: 1995, "Beacon Monitoring Approach to Spacecraft Mission Operations," *First International Symposium on Reducing the Cost of Spacecraft Ground Systems and Operations,* Oxfordshire, UK.